Modeling, forecasting and self-regulation of complex ecological systems

PI: Vadim N. Smelyanskiy, Code IC, NASA Ames; Co-I: Robin D. Morris, RIACS

Goal: Analysis, design and control of self-regulatory dynamical systems to enable prediction of the system's response to changing environmental conditions, and to allow early warning of the breakdown of self-regulation to enable intervention to restore homeostasis.

Objectives: Develop efficient methods for inference of nonlinear stochastic dynamical systems and networks from observations in the space-time domain. Use this method to better understand the self-regulatory mechanisms in complex dynamical networks and the ways to control them.

Key Innovations:

- Computationally efficient algorithm for dynamical model inference:
  - Optimal compensation of dynamical noise
  - Algorithm for learning structure of dynamical networks from data
  - Effective analytical integration
  - Effective algorithm for global minimization

Schedule:

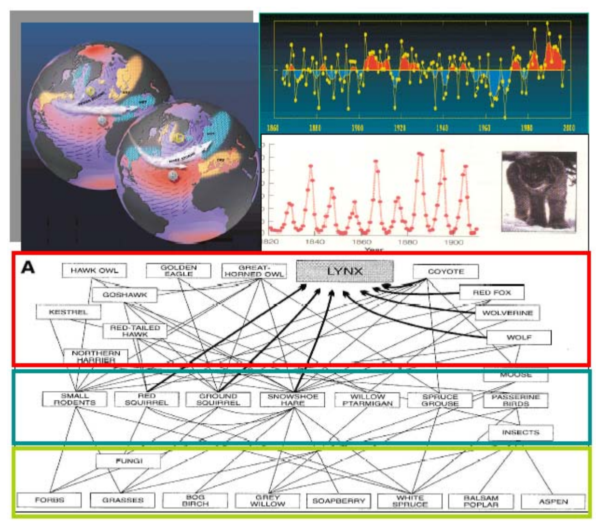
- FY04: Develop efficient method to discover structure of complex self-regulatory dynamical networks; building on proof-of-principle demonstration, develop an understanding of the complex interactions between the closed ecosystem components
- FY05: Improve dynamical network structure learning algorithm to allow it to be applied to systems with very large numbers of components; apply to closed food web ecosystem data from Kluane.
- FY06: Study the effects of external factors and applied controls on self-regulatory behaviour and forecasting of system breakdown.

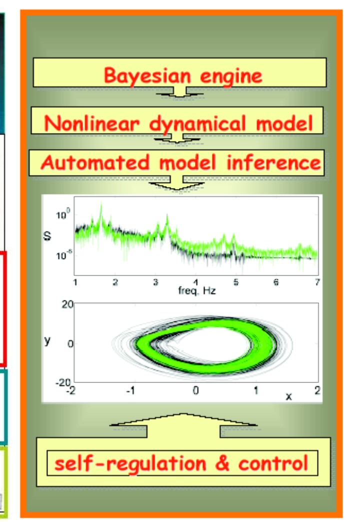
NASA Relevance: Analysis of complex systems enables:

- autonomous monitoring of astronaut cardiovascular system, and prediction of stress related health problems. Also enables early intervention.
- analysis and control of food webs for maintenance of closed ecological systems and understanding their response to changing external conditions - as support for planetary exploration and for understanding life on Earth.

Accomplishments to date:

- Proof-of-principle demonstration: first modeling and prediction in the self-regulatory human cardiovascular system from non-invasive measurements revealing previously unknown interactions.
- Identified systems and data for modeling studies of self-regulatory ecological systems (Kluane boreal forest food web).
- A number of publications and invited talks (see list attached)





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New algorithm for Bayesian inference of complex stochastic nonlinear dynamical systems with noise. Initial algorithm development has been completed. Requires knowledge of the structure of the system. Currently being extended to also learn the structure of the couplings within the system.

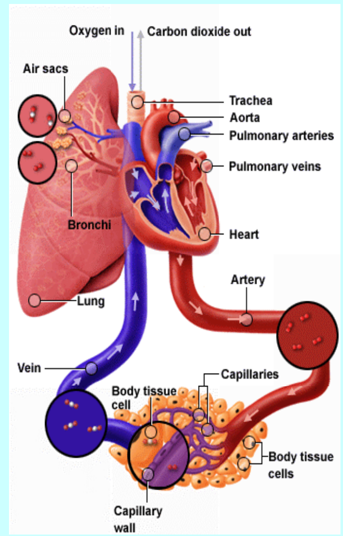
Initial proof-of-principle application domain: non-invasive measurements of the human cardiovascular system.

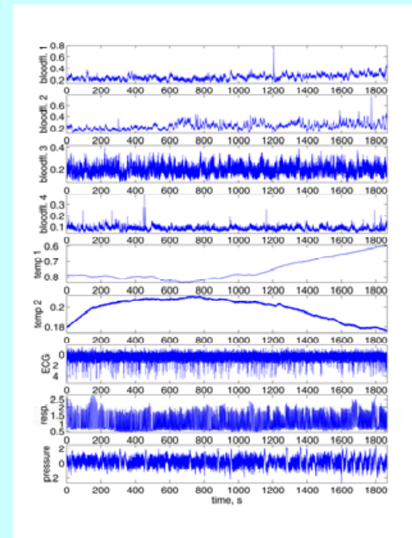
• Applied to the Lancaster University DB of noinvasive measurements of ECG, respiration, blood pressure, cutaneous blood flow, skin temperature for three groups of subjects, healthy, congestive heart failure, beta-blocker treated congestive heart failure. Goal was to infer the noinlinear dynamical system modeling the interaction between the cardiac and respiratory oscillations. Inference was successful, and has uncovered features in the dynamical model that were unknown to the domain scientists (direction of the influence between the cardio and pulmonary oscillations).

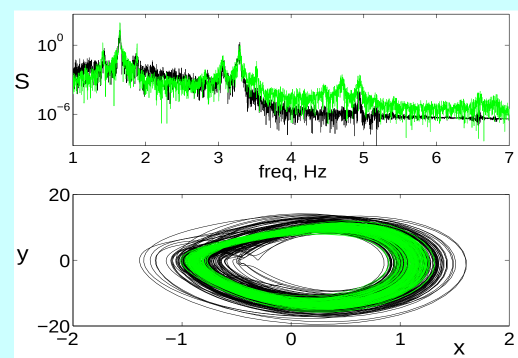
• Shown to give equal diagnostic power as current invasive techniques.

• Applicable to long-term astronaut health monitoring using the cardiovascular vest sensors; enables remote diagnosis of potential cardiovascular problems sufficiently early to enable preventative action.

Collaborators: Prof. P. McClintock (Department of Physics, Lancaster University, Lancaster, UK); Dr P.B.M. Clarkson (Department of Cardiology, Royal Lancaster Infirmary, Lancaster, UK) ; Prof.A. Stefanovska (Faculty of Electrical Engineering, University of Ljubljana, Ljubljana, Slovenia).







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Current and future application domain: food webs as models of closed ecological systems

• Important models of complex interactions between species making up the different tropes in a food web.

• Understanding these interactions can give important information about synchronization, and climactic factors influencing the system.

• Can also be used to analyze, design and control closed self-sustaining ecological life-support systems for human exploration of space. Such as system will necessarily be complex in order to be self-sustaining, and detailed knowledge of its behavior will be needed in order to predict and control deviations from the nominal behavior that will be outside the scope of the system to self-regulate.

• Data available from the Canadian boreal forest ecosystem (especially Kluane study area), including data on the effects of interventions in the system

Collaborators: Dr. M.M. Millonas and Dr. K. Wheeler (Ames Research Center, USA)

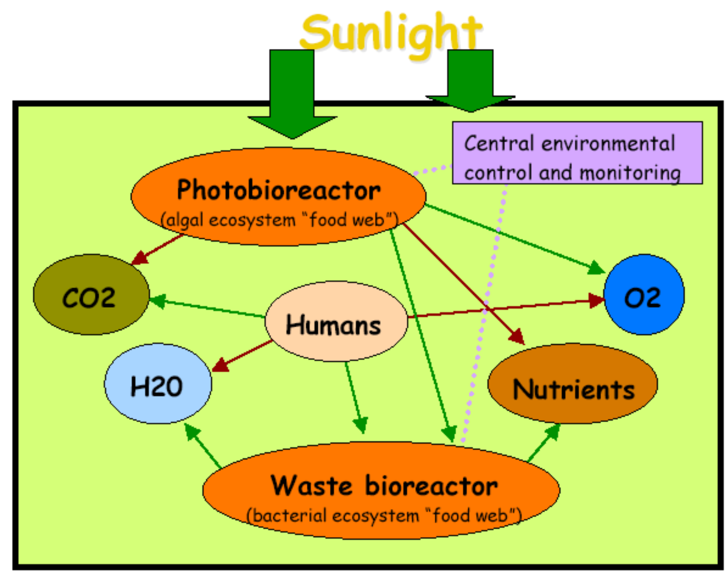
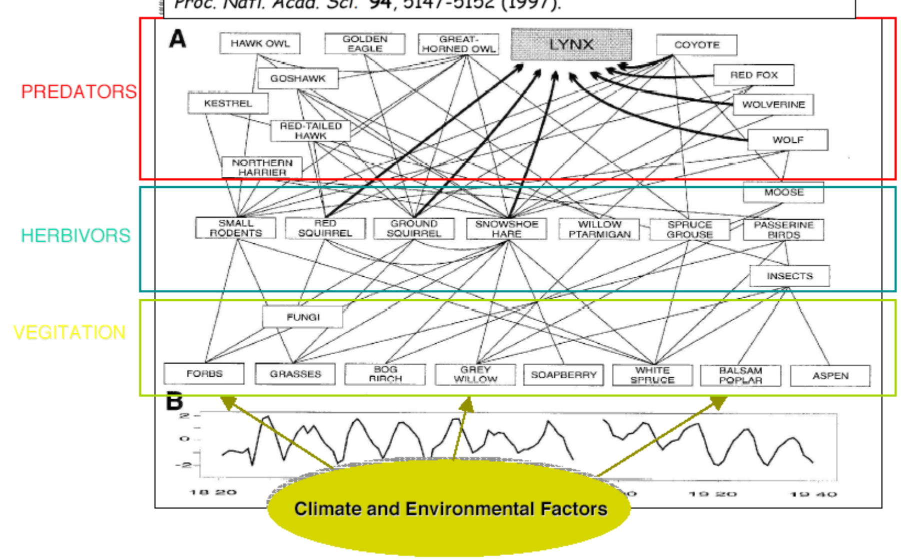


Fig. From: Stenseth et al. Population regulation in snowshoe hare and Canadian lynx: Asymmetric food web configurations between hare and lynx. *Proc. Natl. Acad. Sci.* **94**, 5147-5152 (1997).



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List of publications:

1. V.N. Smelyanskiy, D.A. Timucin, A. Brandrivskyy, D.G. Luchinsky "Model reconstruction of nonlinear dynamical systems driven by noise". Submitted to *Physical Review Letters*.
2. V.N. Smelyanskiy, D.A. Timucin, A. Bandrivskyy, D.G. Luchinsky, P.V.E. McClintock, A. Stefanovska, "Fast Bayesian inference in application to human cardiovascular system", *in proceedings of the third workshop on Physics in Signal and Image Processing*, Grenoble, France, 29-31 january, 2003.
3. A Bandrivskyy, D G Luchinsky, P V E McClintock, V.N Smelyanskiy, A Stefanovska and D A Timucin, "Cardiovascular oscillations: in search of a nonlinear parametric model", in S M Bezrukov, H Frauenfelder and F Moss, ed., *Fluctuations and Noise in Biological*, *Biophysical and Biomedical Systems*, (proceedings of the conference in Santa Fe, June 2003), SPIE, Washington, 2003, pp 271--281.
4. V N Smelyanskiy, D A Timucin, D G Luchinsky, A Stefanovska, A Bandrivskyy and P V E McClintock, ``Time-Varying Cardiovascular Oscillations", in N S Namachchivaya and Y K Lin ed. *IUTAM Symposium on Nonlinear Stochastic Dynamics*, (proceedings of the conference in Allerton Park, University of Illinois, Urbana, August 2002), Kluwer, Amsterdam, 2003, 455--464.

Invited Talks:

1. D.G. Luchinsky, P.V.E. McClintock, V N Smelyanskiy,"Bayesian inference of complex stochastic systems: Noise amplifies the information" (CECAN-ESF Workshop Stochasticity and Sensitivity Lyon, France, May 2003) (**invited talk**)
2. D.G. Luchinsky, V N Smelyanskiy, "Inference of the stochastic nonlinear systems" (Physics Department of The University of Manchester, Manchester, UK, 2003) (invited seminar)
3. D.G. Luchinsky, V N Smelyanskiy,"Model identification from noisy measurements" (Physics Department of The Michigan State University, East Lansing, USA, 2003) (invited seminar)